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AN H_2-O_2 AUXILIARY POWER UNIT FOR SPACE SHUTTLE

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ABSTRACT

Auxiliary power units operating on hydrogen and oxygen have the potential for significantly improved performance and payload for the Space Shuttle vehicles. In order to identify the technologies required for these units and to identify promising system configurations, contracted studies provided component and system-configuration screening analysis and detailed analysis of two preliminary system layouts. From these studies, Lewis Research Center has selected for further investigation a recuperated open-cycle hydrogen-oxygen turbine-driven APU concept with pressure-modulated reactant control. A close-coupled test version of the selected system will be used to experimentally develop needed system technology. This paper discusses the reference system, the control mode, component arrangement, performance potential, and the technology program for this system.

REUSABLE SPACE SHUTTLE VEHICLES, such as the presently planned Orbiter and the reusable Booster studied earlier, require APU's to provide on-board hydraulic and electrical power. This power is required to operate aerodynamic control surfaces, thrust vector controls, landing-gear and airbreathing-engine deployment mechanisms.

Hydrogen and oxygen were initially selected as common propellants for all the Space Shuttle vehicle propellant systems, including the APU. In September of 1970, Lewis Research Center initiated two parallel study contracts (NAS3-11408 and NAS3-14407 by AiResearch Manufacturing Company, a Division of Garrett Corporation and Rocketdyne, a Division of North American Rockwell Company), for the preliminary design of the APU. In Phase I of these studies, AiResearch and Rocketdyne performed parametric studies, configuration studies, and evaluation on the basis of weight, cost and reliability for a variety of H_2-O_2 system concepts as well as monopropellant and other bipropellant systems (1, 3, 4)*. Both contractors selected recuperated H_2-O_2 systems supplied from other on-board high-pressure gaseous-propellant systems as their optimum power systems. The details of the systems selected by each were significantly different.

In Phase II, detailed system analysis and preliminary designs were carried out by each contractor on their recommended optimum system (2, 5, 6, 7). At the end of the 10-month program, both systems were evaluated by NASA-Lewis Research Center and a reference system was synthesized in an effort to combine the best features of both, omit the greatest risks of either, and arrive at a reliable low-weight APU. Subsequent to synthesizing the reference system, a hydrazine fueled APU was base lined for the initial shuttle vehicles. Although heavier than a H_2-O_2 APU of similar peak power and energy output, the hydrazine system represents a lower technology risk. The ongoing Space Shuttle H_2-O_2 APU program will provide the technology base to allow development of a prototype unit. Use of the H_2-O_2 APU in advanced shuttle vehicles would increase payload capability by 1000 to 1500 pounds. Mr. Dale Haine's paper in this session discusses the hydrazine APU. This paper reports the basis for the selection of the reference H_2-O_2 APU and briefly describes the program planned to

*Numbers in parentheses designate References at end of paper.

achieve its technology readiness.

APU REQUIREMENTS

Specific APU requirements for the Space Shuttle vehicles are not yet firmly established. It has, therefore, been necessary for purposes of the preliminary design studies and the recently initiated technology development effort to establish a set of typical requirements, such that the technology developed will be applicable to a range of possible future flight design units. Typical APU requirements were generated by NASA Lewis Research Center based on: (1) the Shuttle Vehicle Phase B contractor projected system needs, and (2) the parametric APU studies completed by AiResearch and Rocketdyne. The significant requirements are stated in table 1.

The 400 hp output level was selected as an approximate midpoint of maximum power level requirements generated during the Shuttle vehicle studies which ranged from about 200 to 600 hp. Propellant supply conditions were established to cover the range of potential supply conditions from pumped cryogenic liquid supplies to high pressure gaseous conditions that might be supplied from other on-board systems. Life requirements were established based on 100 missions of up to three hours APU operation, including three start-stop cycles per mission (start-up prior to launch, shutdown in orbit, restart and shutdown for checkout prior to reentry, startup for reentry and shutdown after landing). These basic numbers were then increased to the stated values to account for hot gas ground checkout operation between missions. The substantial inert gas operation was included to allow for fairly extensive checkout between flights of the complete vehicle hydraulic and electrical systems operating directly off of the APU, without the complexity of the hot gas operation.

The two system configurations generated in the APU study contracts, based on the above requirements, differed primarily in the methods of thermal management and power modulation. These two systems layouts are discussed in the following paragraphs.

SYSTEM No. 1

System No. 1, synthesized by AiResearch Manufacturing Company is schematically represented in figure 1. The hydrogen and oxygen flow first through shutoff valves and pressure regulators to provide 500 psia gas to the APU. A recycle loop provides a flow of heated hydrogen from the recuperator to mix with the low temperature supply to furnish a bulk temperature sufficiently high to prevent congealing the lubricating oil and the hydraulic fluid. Recycle flow rate is varied by a valve to maintain a bulk hydrogen temperature of 400° R into the lubricating oil heat exchanger. A jet ejector pump induces the required flow which first passes through the hydrogen preheater to enhance ejector performance. Downstream of the recuperator the main hydrogen flow is combined with the oxygen for reaction in the combusion chamber. Hydrogen and oxygen flows into the combustion chamber are controlled by electronically linked and separately actuated valves with feedback control to maintain turbine inlet temperature and rotational speed. Combustor pressure is modulated by throttling total flow rate in order to control turbine rotational speed. Combustion temperature is controlled to 2060° R by biasing the oxygen flow rate to vary the (oxygen/fuel) ratio. Combustion products are expanded across a two-stage, pressure-compounded, supersonic turbine to drive two gearbox mounted hydraulic pumps and an alternator. Turbine exhaust products pass through the recuperator and exhaust at a temperature designed to avoid condensation (min. 700° R).

SYSTEM No. 2

System No. 2, baselined by Rocketdyne is shown schematically in figure 2. The incoming hydrogen passes through a pressure regulator and through a recuperator where it is heated by the exhaust from the turbine. A portion of the hydrogen flow is bypassed around the recuperator to provide control of the hydrogen temperature into the power control valve. The heated and bypassed hydrogen both flow through the hydraulic cooler where the necessary hydraulic cooling and further hydrogen heating takes place. A hydrogen bypass controls the desired hydraulic fluid temperature level. The hydrogen next passes through the lube oil cooler, through the hydrogen-oxygen temperature equalizer, and then through the power control valve. The oxygen flows directly from the chosen tankage source through a pressure regulator, which is referenced to the regulated hydrogen pressure, and through the hydrogen-oxygen temperature equalizer. These condition the oxygen so that it arrives at the power control valve at a temperature and pressure close to the hydrogen temperature and

pressure. The power control valve incorporates mechanically linked control elements which deliver the required amount of propellant for maintaining constant turbine speed throughout the range of power levels. Because the state points of both propellants are fixed and equal at the valve entrance, a constant mixture ratio into the combustor is obtained. The temperature of the combustion products is thereby predetermined.

This system was designed for pulse modulation of propellant flow for turbine speed control. This control scheme provides that the control valves are always either fully open or fully closed, with the relative open-closed time period being varied to produce the mean flow rate required to satisfy the power demand. To smooth the delivery, small accumulators are provided ahead of the control valves. The pulse control avoids throttling losses at part load, at the expanse of a very high number of normal operating cycles.

REFERENCE SYSTEM DESCRIPTION AND SELECTION

The results of the two studies were reviewed by a team of Lewis Research Center engineers and a single reference APU configuration was defined. This configuration serves as the initial reference system for the recently initiated H_2-O_2 APU technology development contract. Figure 3 is a schematic of the selected configuration.

The selected configuration incorporates the basic recycle loop from System 1, the H_2-O_2 temperature equalizer and the recuperator bypass from System 2 to provide a controlled combustor inlet temperature, mechanically linked H_2-O_2 throttle valves, pressure-modulated speed control, and a closed loop control of turbine inlet temperature by means of a trim valve in the oxygen line ahead of the throttle valve. This control arrangment combines key features from both control systems. The turbine is a two-stage pressure-compounded supersonic unit which drives the hydraulic pumps and alternator through an oil-mist-lubricated gearbox.

The recycle loop was incorporated in order to minimize the heat exchanger design problems. The recycle flow conditions the hydrogen, which is supplied at temperatures as low as 55° R, to a mixed temperature of 400° R. This arrangement avoids potential problems of congealing oil in the lube oil and hydraulic oil coolers and minimizes potential exhaust condensate freezing problems in the recuperator. Thermal stress and thermal shock problems are also minimized by the reduced temperature differentials in these heat exchangers.

The pressure modulated flow control was adopted in preference to pulse modulation because of its inherently greater reliability, even though pulse modulation offers some reduction in propellant consumption, particularly at part load and low altitude (approximately 50 lbs for the Orbiter mission). The design life of the APU would require approximately 3×10^6 valve cycles as well as 3×10^6 combustor ignition cycles. This type of cyclic life while it may be achievable, is not presently state-of-the-art. Thus pressure modulation (requiring only three on-off cycles per mission and a design life of only 900 cycles) was selected, in spite of the fuel consumption penalty, to achieve higher reliability.

The hydrogen-oxygen temperature equalizer and the recuperator bypass were incorporated to provide constant inlet temperatures to the combustor. The recuperator bypass is controlled to provide a constant hydrogen temperature to the combustor and the equalizer matches the oxygen temperature to the hydrogen temperature. The use of fixed combustor inlet temperatures along with equal pressures would in theory allow the use of open loop turbine inlet temperature control. That is, the controlled supply conditions along with well matched linked throttle valves would provide a constant O/F and constant turbine inlet temperature. However any malfunctions or fabrication variations causing deviations in temperatures, pressure equalization, or valve matching would result in an uncontrolled turbine inlet temperature deviation. Thus the oxygen trim valve was incorporated, controlled by a turbine inlet temperature sensor, to provide a closed loop turbine inlet temperature control.

Mechanically linked throttle valves were chosen over valves which were mechanically independent but electronically coordinated. The mechanically linked valves assure simultaneous operation and thus good O/F ratio control, particularly during rapid power transients.

With closed loop turbine inlet temperature control the temperature control provided by the recuperator bypass and temperature equalizer is not essential. However, it does reduce substantially the normal required control range of the oxygen trim valve and may substantially ease the problem of achieving a satisfactory, practical control system. In addition, the

throttle valve operates at a constant temperature and a substantially cooler temperature than the peak temperature that would be experienced with full flow recuperation.

Another feature of the recuperator bypass is that in addition to controlling the combustor inlet temperature it is also controlling the temperature of the secondary flow to the recycle loop to essentially the same value. Since this secondary flow is mixed with the primary flow to provide a constant 400° R temperature to the oil cooler, it is obvious that increasing the secondary flow temperature will result in a lower secondary flow rate to achieve the 400° R. This then lowers the total flow in the recycle loop and reduces the cooling capacity of the system. This effect is shown in figure 4. Thus the temperature set point for the recuperator bypass may be adjusted, within limits, to adjust the cooling capacity. However, reducing recuperation to increase recycle flow and cooling capability results in reduced efficiency and increased fuel consumption. It is a very desirable feature, however, for tailoring the APU to specific vehicle cooling needs.

REFERENCE SYSTEM SIZE, WEIGHT AND PERFORMANCE

While the selected reference system has not yet been analyzed in detail, its size, weight and performance can be estimated from the results of analysis of the two systems from which it was synthesized. On this basis, it is estimated that the reference APU (excluding hydraulic pumps and alternator) would require a volume of approximately $1\frac{1}{2}$ feet by 2 feet by $2\frac{1}{2}$ feet and would have a fixed weight of approximately 200 pounds. Estimated propellant consumption curves are shown in figure 5, for sea level and orbital operation. As can be seen, integrated mission SPC will be heavily dependent on the amount of operation at low power levels and at sea level ambient conditions. Assuming substantial low power operation, the mission SPC will likely be in the range of 2 to 2.5 lbs/hp-hr.

TECHNOLOGY PROGRAM

An H_2-O_2 APU system technology contract is being conducted by AiResearch under Contract NAS3-15708. This effort will start with an analysis of this selected reference system in sufficient detail to define any necessary modifications, and will establish a viable detail design of the reference system. Following completion of this reference system design a test system (APU-T) will be designed which can be utilized to investigate the critical technology areas of the H_2-O_2 APU. These critical technology areas are primarily system problems involving thermal management, propellant conditioning, and controls. Therefore in the APU-T test system all components, except the gearbox, will be "flight type" designs sufficiently close-coupled to achieve realistic dynamic performance. Testing of the APU-T will be conducted to evaluate steady state and dynamic performance of the reference system over the full range of operating conditions. In addition tests will be performed to further evaluate other system options including elimination of combustor inlet temperature control (by operating without the recuperator bypass and temperature equalizer) and operation with pulse rather than pressure modulated control. As the test program progresses the reference system design will be maintained and modified as necessary to incorporate test results. This activity will include the generation and maintenance of a digital-computer steady-state and dynamic model of the reference system to predict its performance and permit modeling of system modifications. The resultant computer program will be a delivered end item of the contract. Upon completion of the test program two APU-T systems will be delivered to NASA Lewis Research Center, along with a final reference system design which could serve as the technology base for the development of a hydrogen-oxygen fueled APU for the Space Shuttle.

One key technology area, not included in the system technology contract, is the problem of establishing the technology for a flight type hydrogen pump to be able to supply liquid hydrogen to the APU. A five cylinder piston pump with similar requirements to those for an APU pump was designed and fabricated by Cosmodyne Incorporated for the General Electric Company as a portion of a turbojet engine fuel control. This pump will be tested to determine the capability of this type of unit to meet the performance and net positive suction head requirements of the APU application. If these tests are successful, a limited endurance and thermal cycling test is planned to provide a preliminary evaluation of the life capability of this multiple piston unit.

CONCLUDING REMARKS

This H_2-O_2 APU technology program is designed to explore and develop the critical technology which will make it possible to confidentially select an H_2-O_2 APU in place of a hydrazine APU for application to future shuttle vehicles. This will allow improved versions of the space shuttle vehicles to take advantage of the reduced propellant consumption, to increase vehicle payload capability, and to gain the potential for minimizing maintenance offered by the H_2-O_2 APU. This technology program is intended to advance APU technology to the point at which prototype APU development may be undertaken. Successful completion of this program should also provide a firm technology base for future development of H_2-O_2 engines for other applications.

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Table 1 - Shuttle Hydrogen-Oxygen APU Requirements

Requirement	Applicable specification
Power output (net)	25 hp idle to 400 hp max. (2 hydraulic pumps at 5,000 rpm; 1 alternator at 12,000 rpm)
Waste heat recuperation	
Internally generated heat dissipated into hydrogen, including a constant 35 Btu/sec hydraulic fluid cooling	
Propellant supply conditions:	
Pressure, psia	1,000 to 500
Temperature, ^{o}R	
Hydrogen	55 to 560
Oxygen	275 to 560
Control:	
Turbine inlet temperature, ^{o}R	2060
Rotational speed, rpm	70,000
Response	±5% max. speed variation with full range power change (between idle and max.) in 0.075 sec
Life:	
Hydrogen-oxygen operation	1,000 hr and 900 start-stop cycles
Inert gas operation for ground checkouts	2,000 hr and 600 start-stop cycles

AiRESEARCH
SPACE SHUTTLE HYDROGEN-OXYGEN APU SYSTEM

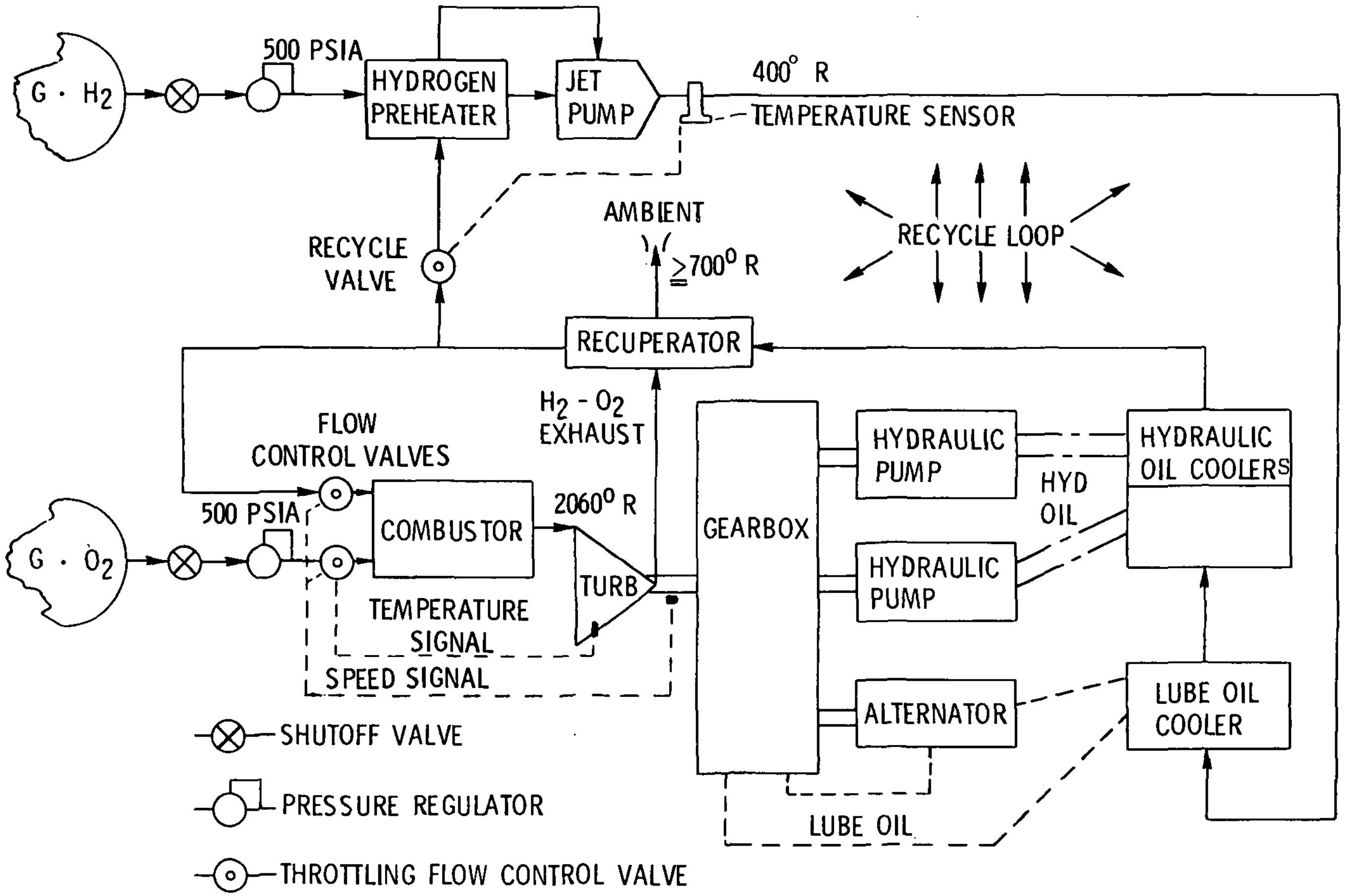

Figure 1.

ROCKETDYNE

SPACE SHUTTLE HYDROGEN-OXYGEN APU SYSTEM

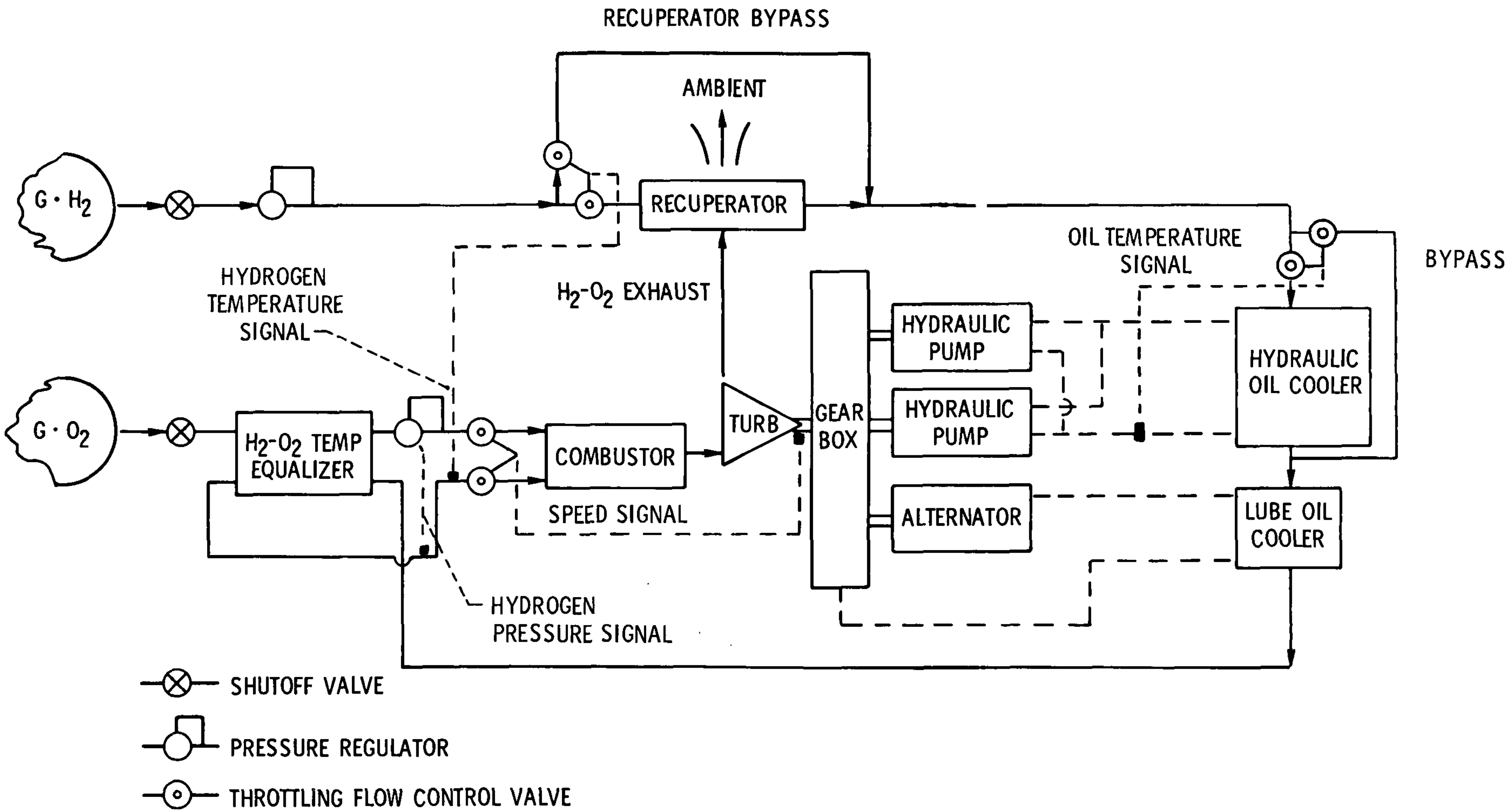

Figure 2.

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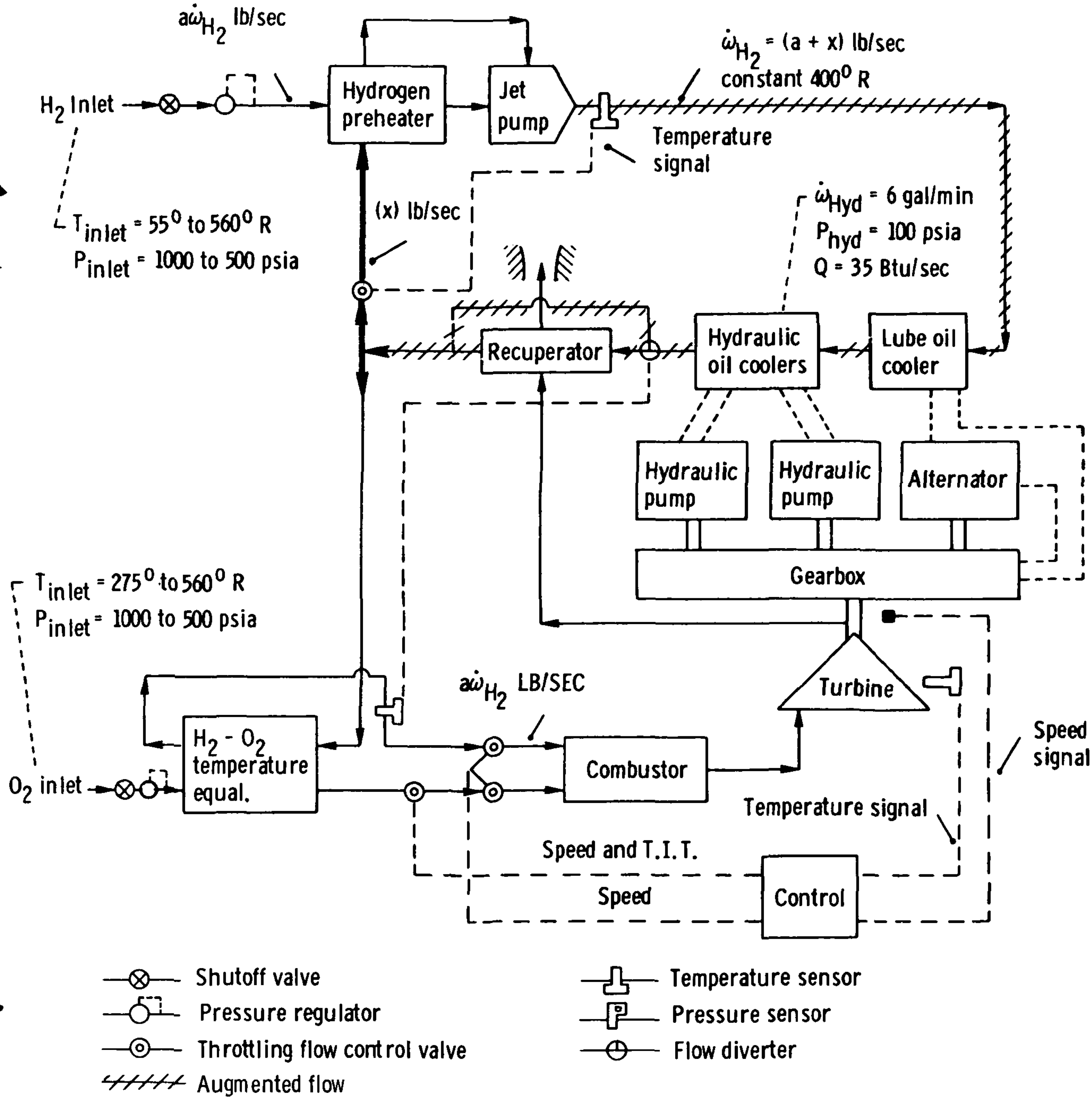

Figure 3. - Initial reference system schematic. NASA LeRC selection.

EXHIBIT "A"

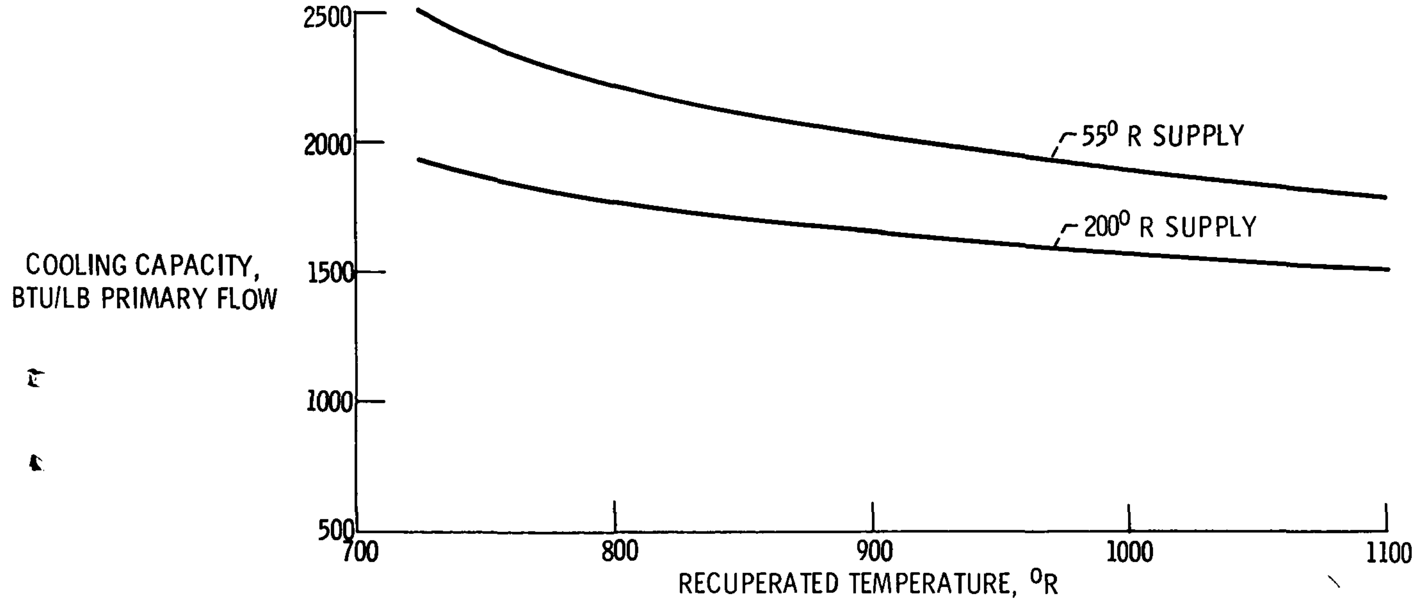

Figure 4. - Cooling capacity versus recuperated temperature.

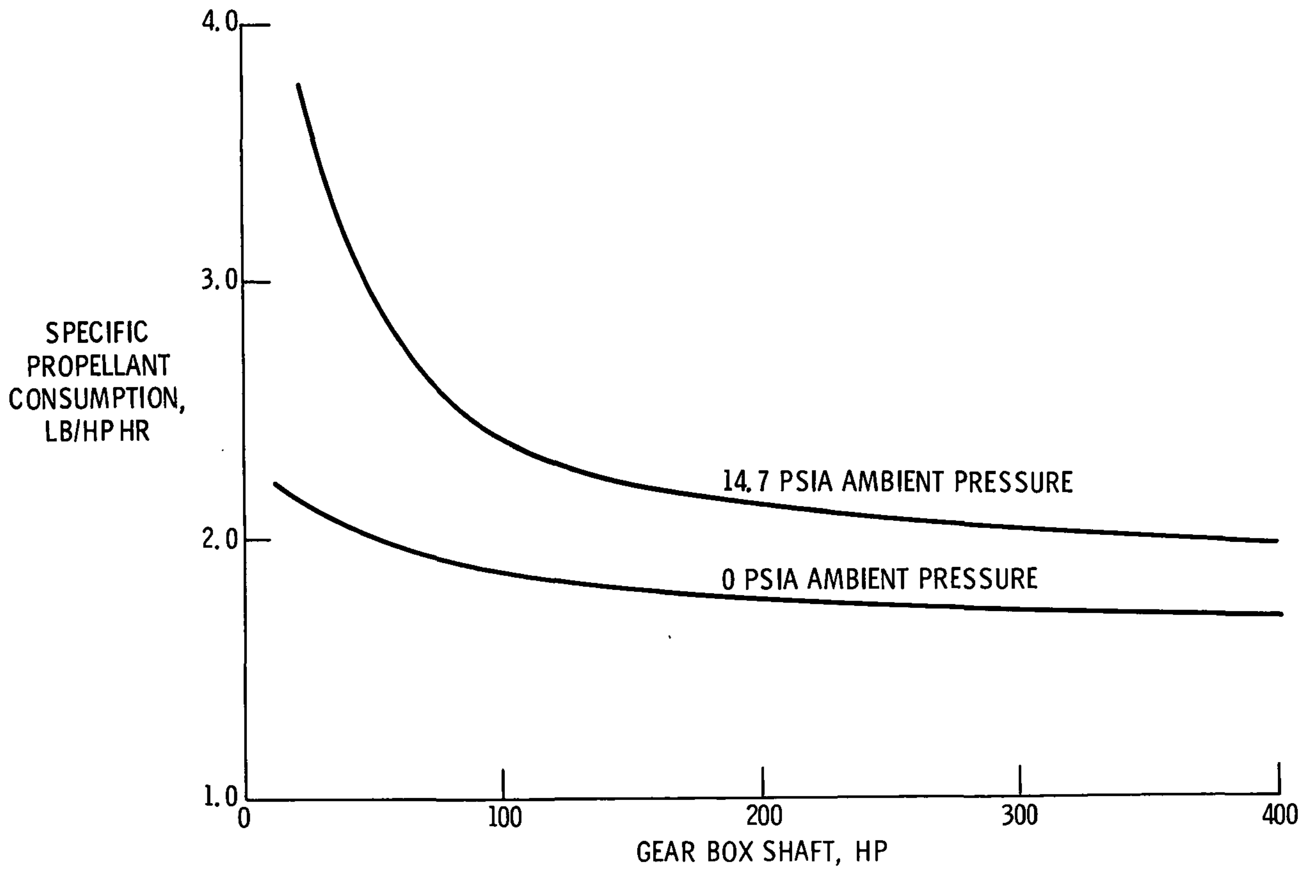

Figure 5. - Specific propellant consumption versus gear box output power for H_2-O_2 with O/F = 0.665 (900^0 R recuperated combustor inlet).